DES Science Requirements and the Science Case for Small Telescope Auxiliary Calibrations

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DARK ENERGY SURVEY

The DES Photometric System

The DES photometric system is defined as the system response functions $T_b(\lambda)$ for the five bands $b=(g, r, i, z, y)$. The magnitude in a band b is thus

$$m = -2.5\log\left(\frac{F_b}{3631Jy}\right) \qquad (5)$$

where F_b is object flux convolved with the system response,

$$F_b = \int F_\nu(\lambda) \mathrm{T}_b(\lambda) d\lambda \qquad (6)$$

$F_b(\lambda)$ is the flux of an object at the top of the atmosphere, $T_b(\lambda)$ are the normalized system response functions,

$$\mathrm{T}_b(\lambda) = \frac{\lambda^{-1} S_b(\lambda)}{\int \lambda^{-1} S_b(\lambda) d\lambda} \qquad (7)$$

and $T_b(\lambda)$ are the system response functions. The system response includes the transmission of a standard atmosphere at a fiducial airmass of 1.2. The system response S_b need only be measured relative to the response at a fiducial wavelength as the absolute normalization cancels in equation (7). In the wide area survey, our need to establish our magnitude zeropoint, as in eq (5), is not as well motivated as our need to establish our relative magnitudes $m_1 - m_2 = -2.5log(F_{b1}/F_{b2})$ inside a bandpass, and our need to establish colors $m_b - m_c = -2.5log(F_b/F_c)$ across bandpasses.

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DES Science Requirements

R-17 For each of the *g, r, i, z*, and *Y* bandpasses of the wide-area survey, the rms fluctuations in the spatially varying systematic component of the magnitude error in the final co-added catalog must be smaller than 2% over all scales smaller than 4 degrees.

"Internal Calibration"

R-18 The relative magnitude zeropoints between bandpasses averaged over the survey must be known to 0.5%. The magnitudes will be on the natural instrument system.

"Relative Calibration"

R-19 The magnitude zeropoint of the individual bandpasses and individual images, averaged over all images in the survey must be known to 0.5%. This is not a requirement on knowing the absolute energy flux.

"Absolute Calibration"

R-20 The system response curves (CCD + filter + lenses + mirrors + atmosphere at 1.2 airmasses) must be known with sufficient precision that the calculated *grizY* magnitudes of an object with a precisely calibrated spectrum agree with the measured magnitudes to within 2%. When averaged over 100 object samples uniformly distributed over the focal plane, the residuals in magnitudes due to uncertain system response curves should be < 0.5%.

"System Response"

G-4 A goal of the survey is to achieve **R-17** at the enhanced level of 1% for the final co-added catalog.

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Photometric calibration methods

All-Sky Photometry

"Method 1"

The first method is the traditional one in astronomy, used in cases ranging from single observations to the SDSS. It seeks for each bandpass and each night a least squares solution to a model:

$$m = m_I + m_o + kX + a(B-V) + b(B-V)X + O(X^2) \qquad (1)$$

where m is the calibrated magnitude, m_I is the instrumental magnitude $m_I = -2.5\ log(\mathrm{DN})$, DN is the measured counts in an object, m_o is the zeropoint that takes m_I of, say, a 20th mag star to $m=20$, X is the airmass, k is the extinction coefficent, $(B\text{-}V)$ is a traditional measure of the color of the object and here stands for the color measured in DES bandpasses near the bandpass of interest, and a and b are, like m_o and k, parameters to be found in the least squares fit. The model contains terms for the instrument, m_o, the atmosphere, m_o and b, and terms for the spectrum of the object of interest convolved with the instrumental system response, a and b. The primary objective of this method is to solve for the extinction coefficient k so that observations taken at a variety of airmasses X may be combined to solve for a single zeropoint, m_o. In practice parameters m_o and k are correlated: if observations are taken at a single airmass the term kX is subsumed into m_o. Also in practice it is rare to observe enough standard stars to solve for the model parameters with an accuracy, as opposed to precision, of better than 2%. The terms with $O(X^2)$ with may be appreciable at 1%. A strength of this procedure is that since it produces a model for the night any observation taken that night may be calibrated, regardless of its spatial location.

Performed on a night by night basis.

Aims to solve for internal, relative, and absolute calibration.

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Relative Photometry

surveys. It seeks to solve simultaneously for the relative zeropoints of all images taken in a single bandpass in the survey, again using a least squares solution, solving:

$$m = m_o + \sum_i \Delta m_i \qquad (2)$$

where m is as before, m_o is the zeropoint, here defined to be m_I on a fiducial CCD, $\Delta m_i = m_{I,i} - m_o$, $m_{I,i}$ is the instrumental magnitude on CCD i, and m_I and DN are as before. This is better written as a matrix least squares problem:

$$\mathbf{y} = \tilde{\mathbf{A}}\mathbf{x} + \mathbf{n} \qquad (3)$$

where $\boldsymbol{x}$ is the vector of (relative) zeropoints to be soved for, $\mathbf{n}$ is the noise vector, $\mathbf{y}$ is the vector of the observed $\Delta m_{ij} = m_{I,i} - m_{Ij}$ and $\mathbf{A}$ is the observation matrix connecting overlapping CCD pairs. This is to be evaluated for all images taken in a given filter. There are 1666 hexes in a single tiling, and after the first year there will be 2 tilings per filter. There are 62 CCDs in a single camera image of a hex. Thus at the end of year one $\boldsymbol{y}$ is a 1666*2*62= 206548 length vector consisting of $\sum_j \Delta m_{ij}$ for a single CCD i of a single exposure with the overlapping CCD j's from another exposure. Define overlap to be images that overlap by more than 10^6 pixels. The Δm_{ij} are made by finding the single flux ratio value offset between all the objects in the overlap.The 206548x206548 observation matrix $\mathbf{A}$ consists of ones and zeros: ones where the CCDs from the target image overlaps other images. This matrix is very sparse and mostly banded which is important for efficient computations. Both vectors $\boldsymbol{x}$ and $\mathbf{n}$ are of length 206548 and element by element refer to the same CCD and exposure. In $\mathbf{n}$ are suitable noises, say the variance of the sky noise. The vector $\boldsymbol{x}$ is to be solved for and provides the zeropoints to add to the m_I to produce a flat map. There are many ways to solve for this map (see e.g., Tegemark ApJ 487 L87, 1997). Most use as weights the covariance matrix. The standard solution in linear algebra textbooks is:

$$\mathbf{x} = (\tilde{\mathbf{A}}^T \tilde{\mathbf{C}} \tilde{\mathbf{A}})^{-1} \tilde{\mathbf{A}}^T \tilde{\mathbf{C}} \mathbf{y} \qquad (4)$$

where $\mathbf{C}$ is the covariance matrix. The primary objective of this method is to use repeated observations of stars to find the zeropoints which produce the least squares residuals for the relative photometry over the survey map. This method argues that the atmosph

"Method 2"

Performed on entire survey.

Aims to solve for internal calibration.

Calibration in other surveys

DARK ENERGY SURVEY

All-Sky Photometry

COSMOS- Subaru SuprimeCam

THE ASTROPHYSICAL JOURNAL SUPPLEMENT SERIES, 172:9–28, 2007 September

THE COSMIC EVOLUTION SURVEY (COSMOS): SUBARU OBSERVATIONS OF THE *HST* COSMOS FIELD[1]

Y. Taniguchi,[2] N. Scoville,[3,4] T. Murayama,[5] D. B. Sanders,[6] B. Mobasher,[7] H. Aussel,[8] P. Capak,[3] M. Ajiki,[5] S. Miyazaki,[9] Y. Komiyama,[10] Y. Shioya,[2] T. Nagao,[10,11] S. S. Sasaki,[2,3,5] J. Koda,[3] C. Carilli,[12] M. Giavalisco,[13] L. Guzzo,[14] G. Hasinger,[15] C. Impey,[16] O. LeFevre,[17] S. Lilly,[18] A. Renzini,[19] M. Rich,[20] E. Schinnerer,[21] P. Shopbell,[3] N. Kaifu,[10] H. Karoji,[10] N. Arimoto,[10] S. Okamura,[22] and K. Ohta[23]
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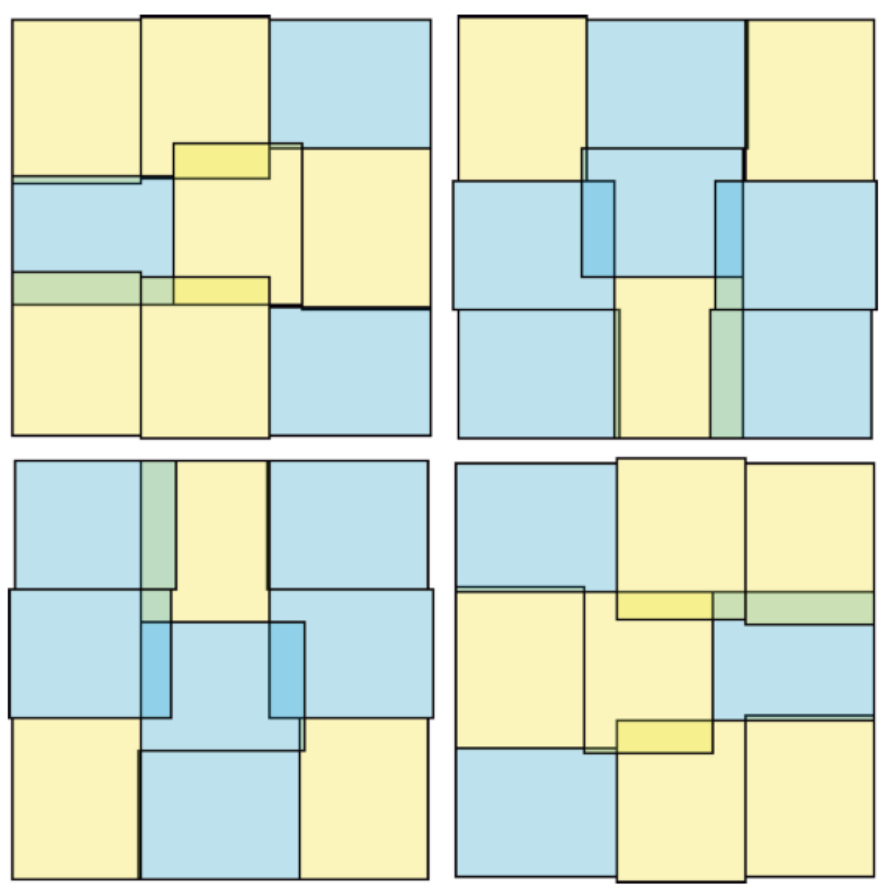

Fig. 2.—Dithering pattern C.

Dither pattern with small overlapping edges

2.2.2. *Scattered-Light Correction*

Mechanical and optical constraints make it impossible to baffle wide-field cameras against all scattered light. The scattered light is equivalent to an unknown dark current added to each image, and must be subtracted rather than divided out. As a result, the usual flat-fielding technique of observing a uniform light source such as the dome or sky is inaccurate at the 3%–5% level.

For Suprime-Cam the scattered-light pattern and strength change significantly with the lighting conditions and telescope position. Variations as large as ±5% are observed at the edges of the field between dark, twilight, and dome conditions. Figure 5 shows the difference between two dome flats taken at different rotation angles. This effect is similar in amplitude and pattern to that observed with the 12K and Megacam cameras on the CFHT.[37]

COSMOS- Subaru SuprimeCam

Scattered light correction map

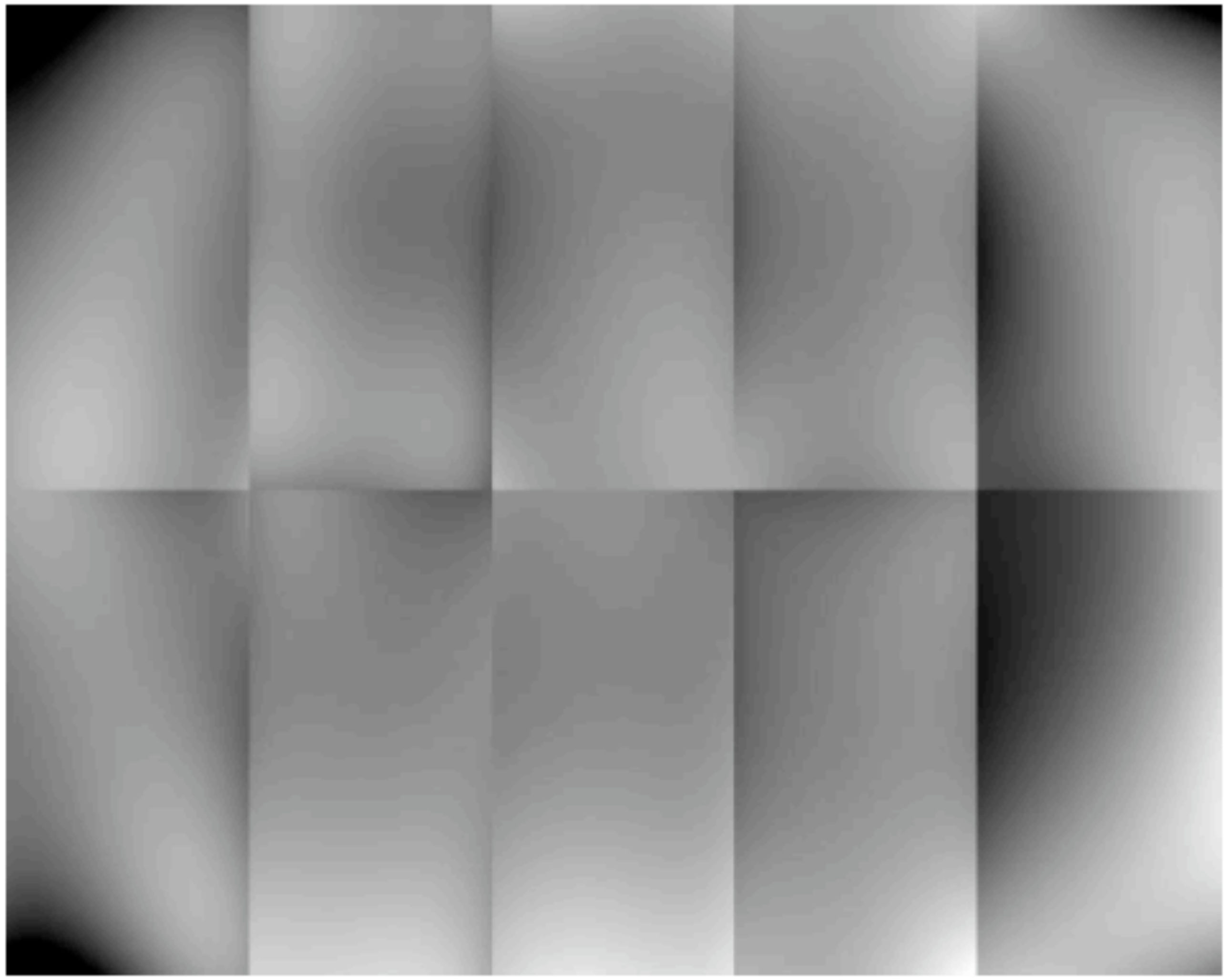

FIG. 6.—Relative correction to the r^+ Suprime-Cam dome flat with chip-to-chip sensitivity variations removed. The scale is linear with a stretch of −3% to +3% from black to white. A correction for scattered light in the vignetted portion of the field is clearly visible around the edge of the field of view.

For a single object the real magnitude $M_{\rm real}$ is described by

$$M_{\rm real} = M + C_r + P_e, \quad (1)$$

where M is the measured magnitude. If we consider a pair of exposures, a and b, we can construct a χ^2 relation as

$$\chi^2 = \sum_{a=0}^{\rm Nexp} \sum_{b=a+1}^{\rm Nexp} \sum_{i=o}^{\rm Nobj} \frac{(M_{i,a} - M_{i,b} + C_{r,a} - C_{r,b} + P_a - P_b)^2}{\sigma_{i,a}^2 + \sigma_{i,b}^2}, \quad (2)$$

which can be minimized to obtain the C_r and P_e factors. Since an object can only belong to one region in each exposure we use the notation $C_{r,a}$ to indicate the region an object belongs to in exposure a.

scattered light corrections

Measured magnitudes

zeropoints

DARK ENERGY SURVEY

Auxillary Telescope+
Relative Photometry

SDSS Stripe 82: Industrial 1% Photometry

The Astronomical Journal, 134:973–998, 2007 September

Many repeat observations of the same area.

SLOAN DIGITAL SKY SURVEY STANDARD STAR CATALOG FOR STRIPE 82: THE DAWN OF INDUSTRIAL 1% OPTICAL PHOTOMETRY

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Photometric errors computed by the photometric pipeline provide a good estimate of random errors in SDSS photometry, as demonstrated by the χ^2 distributions shown in Figure 1. However, the measurements are also subject to systematic errors such as spatial dependence of the internal zero points (calibration errors) and the overall deviations of the internal SDSS zero points from an AB magnitude scale. Formally, the true AB magnitude of an object (defined by eq. [1]) in a given band, $m_{\rm true}$, can be expressed as

$$m_{\rm true} = m_{\rm cat} + \delta_m({\rm R.A., decl.}) + \Delta_m, \quad (4)$$

where $m_{\rm cat}$ is the cataloged magnitude, δ_m(R.A., decl.) describes the spatial variation of the internal zero-point error around Δ_m (thus, the average of δ_m over the cataloged area is zero by construction), and Δ_m is the overall (spatially independent) deviation of the internal SDSS system from a perfect AB system (the five values of Δ_m are equal for all the cataloged objects). Here we ignore systematic effects, e.g., device nonlinearity and bandpass variations between different camera columns, which depend on individual source properties such as brightness and color (but see § 2.5.2 below).

Break problem up into “internal calibration” and “relative calibration” parts

The spatial variation of the internal zero-point error can be separated into “color” errors, relative to a fiducial band, say r, and an overall “gray” error (e.g., unrecognized temporal changes in atmospheric transparency due to gray clouds),

$$\delta_m({\rm R.A., decl.}) = \delta_r({\rm R.A., decl.}) + \delta_{mr}({\rm R.A., decl.}). \quad (5)$$

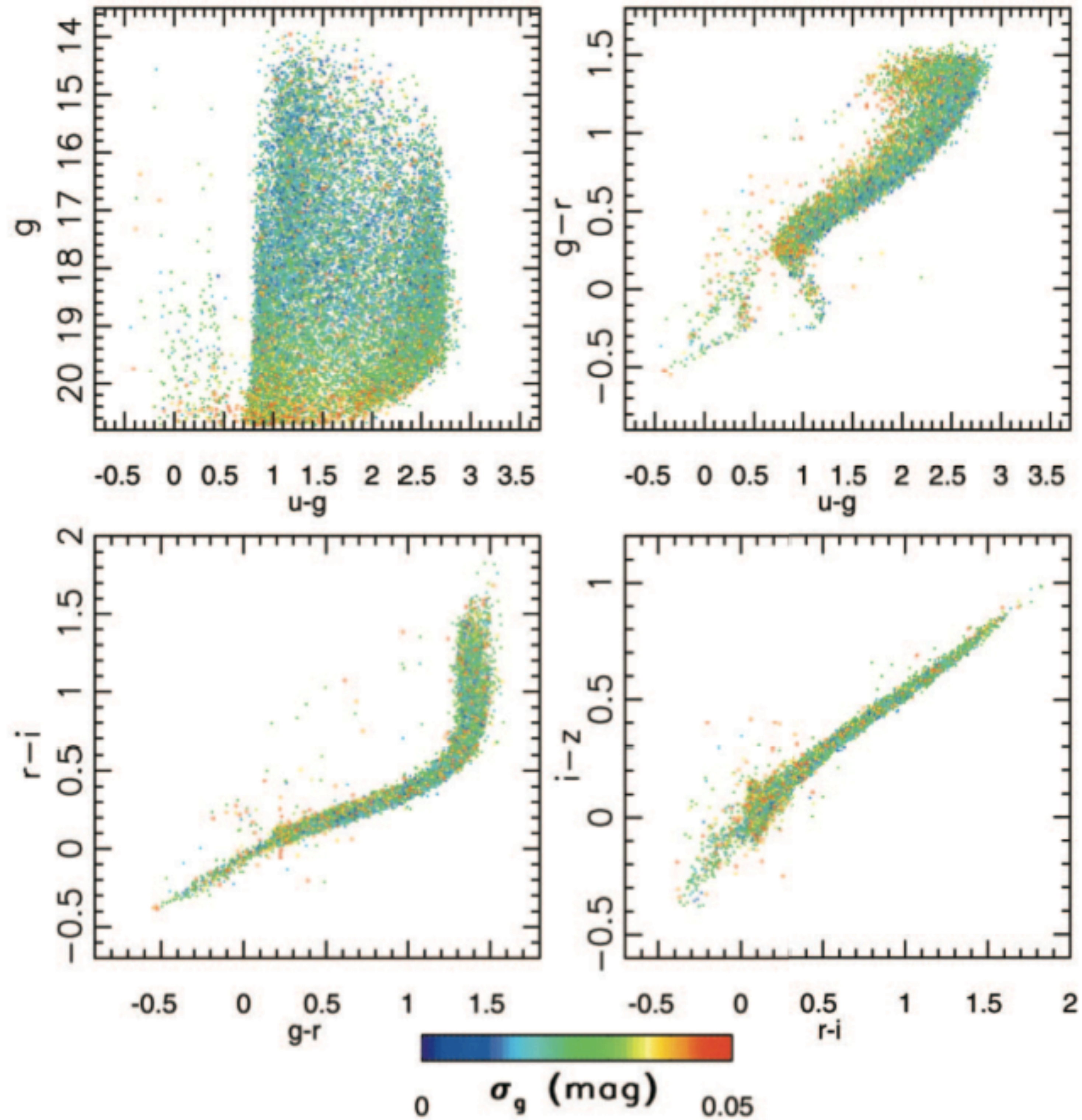
Below, we discuss methods for estimating both the gray error δ_r(R.A., decl.) and the color errors δ_{mr}(R.A., decl.).

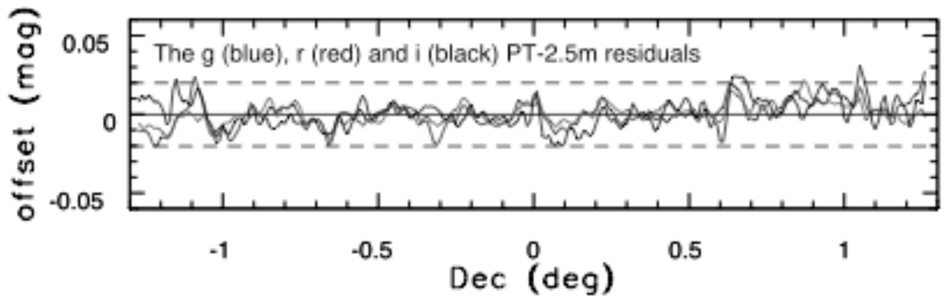
The deviation of the internal SDSS system from a perfect AB system, Δ_m, can also be expressed relative to the fiducial r band,

$$\Delta_m = \Delta_r + \Delta_{mr}. \quad (6)$$

Break problem up into “absolute calibration” and “relative calibration” parts

SDSS Stripe 82: Industrial 1% Photometry





Average the repeat magnitudes

Use PT photometry to get single bandpass absolute and internal calibration part.

Use star colors to get relative calibration part.

Relative Photometry

DARK ENERGY SURVEY

SDSS Uber-calibration

AN IMPROVED PHOTOMETRIC CALIBRATION OF THE SLOAN DIGITAL SKY SURVEY IMAGING DATA

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ABSTRACT

We present an algorithm to photometrically calibrate wide-field optical imaging surveys, which simultaneously solves for the calibration parameters and relative stellar fluxes using overlapping observations. The algorithm decouples the problem of "relative" calibrations from that of "absolute" calibrations; the absolute calibration is reduced to determining a few numbers for the entire survey. We pay special attention to the spatial structure of the calibration errors,

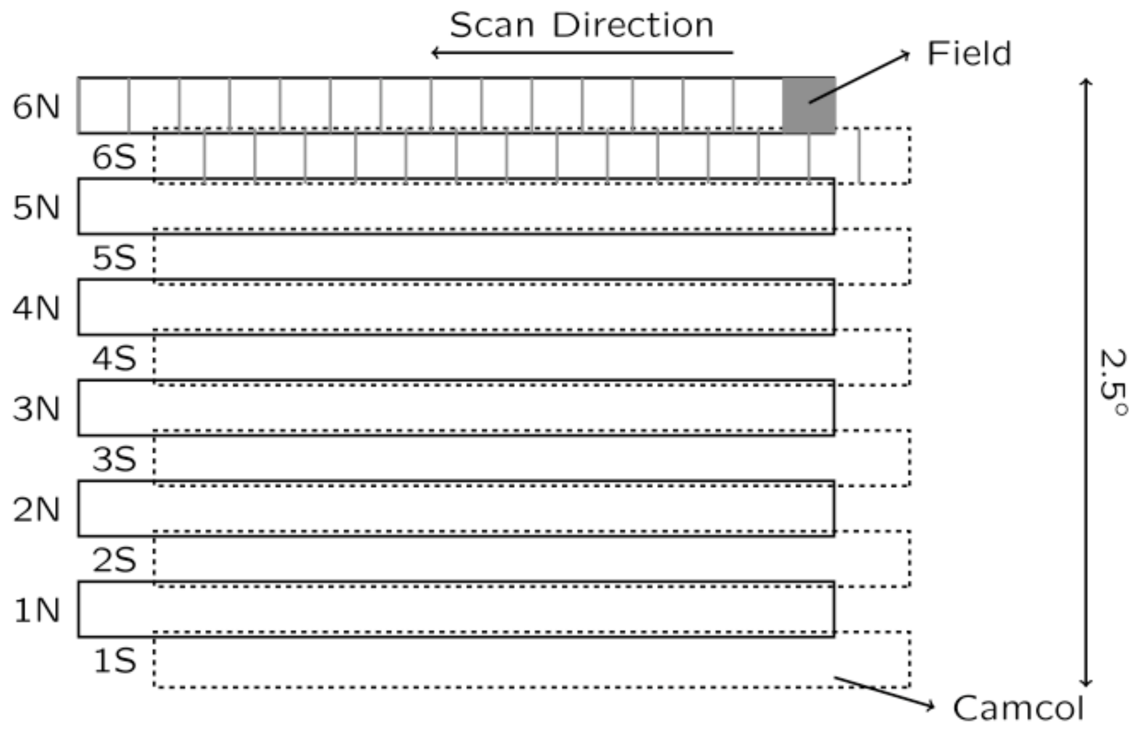


Fig. 1.—Geometry of the SDSS imaging. Part of an SDSS stripe with the two interleaved strips (denoted by N and S) is shown. Each strip consists of six camcols (numbered 1 through 6 in the figure), while each camcol is further divided into fields (for simplicity, we show field divisions for only two camcols). See the text for more details.

Stripe pattern with small overlapping edges

DARK ENERGY SURVEY

SDSS Uber-calibration

3.2. *Solution*

Having specified the parameters of the photometric model, we now turn to the problem of determining them. It is natural to consider repeat observations of stars to constrain these parameters.[19] Let us therefore consider $n_{\rm obs}$ observations with observed instrumental magnitudes $m_{{\rm ADU},j}$, of $n_{\rm star}$ unique stars with unknown true magnitudes m_i. Note that $n_{\rm obs}$ is the number of observations of *all* stars, i.e., $n_{\rm obs} = \sum_{i=1}^{n_{\rm star}} n_i$, where n_i is the number of times star i is observed. Using equation (6), we construct a χ^2 likelihood function for the unknown magnitudes and photometric parameters,

$$\chi^2\left[a_\alpha, k_\beta, (dk/dt)_\beta, f_\gamma\right] = \sum_i^{n_{\rm star}} \chi_i^2, \qquad (7)$$

Measured mags

Instrumental mags

atmosphere

$$\chi_i^2 = \sum_{j \in \mathcal{O}(i)} \left[\frac{m_i - m_{j,{\rm ADU}} - a_{\alpha(j)} + k_{\beta(j)}(t)x - f_{\gamma(j)}}{\sigma_j}\right]^2, \qquad (8)$$

flat field

where j runs over the multiple observations, $\mathcal{O}(i)$, of the ith star, σ is the error in $m_{j,{\rm ADU}}$, and $k(t)$ is given by equation (5). We also assume that errors in observations are independent; this is not strictly true as atmospheric fluctuations temporally correlate different observations. One can generalize the above to take these correlations into account, and, as we show below, our results are not biased by this assumption. Note that equation (7) has $n_{\rm obs}$ known quantities and $n_{star} + n$(parameters) unknowns. In general, the number of photometric parameters is $\ll n_{\rm star}$, and $n_{\rm obs} > 2n_{\rm star}$, implying that this is an overdetermined system.

Then substituting equation (10) into equation (8) yields a matrix equation for χ^2,

$$\chi^2 = (\boldsymbol{Ap} - \boldsymbol{b})^t \boldsymbol{C}^{-1} (\boldsymbol{Ap} - \boldsymbol{b}), \qquad (12)$$

where $\boldsymbol{A}$ is an $n_{\rm obs} \times n_{\rm par}$ matrix, $\boldsymbol{b}$ is an $n_{\rm obs}$ element vector, and $\boldsymbol{v}^t$ represents the transpose of $\boldsymbol{v}$. The errors are in the covariance matrix $\boldsymbol{C}$, which, in equation (8), is assumed to be diagonal (but can be generalized to include correlations between different observations). For clarity, we explicitly write out the form of $\boldsymbol{Ap} - \boldsymbol{b}$ for the case of a single star observed twice at air mass x_1 and x_2, and with errors σ_1 and σ_2, where only the a- and k-terms are unknown,

$$\left[\begin{pmatrix} 1 & 0 & -x_1 & 0 \\ 0 & 1 & 0 & -x_2 \end{pmatrix} - \begin{pmatrix} I_1 & I_2 & -x_1 I_1 & -x_2 I_2 \\ I_1 & I_2 & -x_1 I_1 & -x_2 I_2 \end{pmatrix}\right] \begin{pmatrix} a_1 \\ a_2 \\ k_1 \\ k_2 \end{pmatrix}$$

$$- \begin{pmatrix} m_{1,{\rm ADU}} - m_{1,{\rm ADU}} I_1 - m_{2,{\rm ADU}} I_2 \\ m_{2,{\rm ADU}} - m_{1,{\rm ADU}} I_1 - m_{2,{\rm ADU}} I_2 \end{pmatrix}, \qquad (13)$$

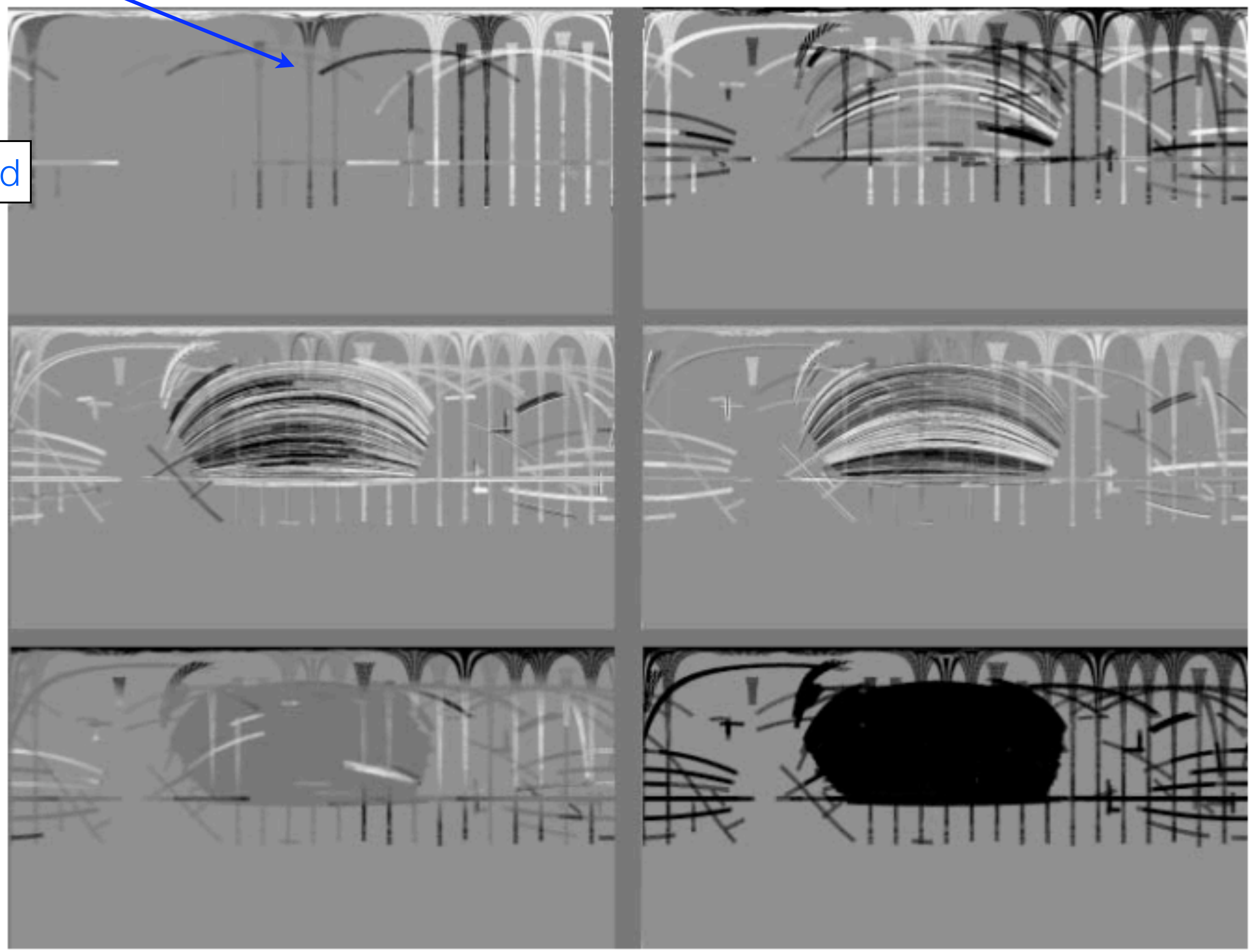
where I_i is the normalized inverse variance, $I_i = \sigma_i^{-2} / \sum_j \sigma_j^{-2}$. Each row of $\boldsymbol{Ap} - \boldsymbol{b}$ has a simple interpretation as the difference between the magnitude of a particular observation of a star and the inverse variance weighted mean magnitude of all observations of that star. Also, although $\boldsymbol{A}$ is a large matrix ($\sim$50,000,000 $\times$ 2000 for the SDSS), it is extremely sparse and amenable to sparse matrix techniques.

DAI
SUI

Residual uncertainities

Ancillary data

Best constrained



Least constrained
an overall zp

FIG. 10.—Examples of the spatial structure in the calibration errors for the r band, organized from left to right and top to bottom in increasing order of their uncertainties. The top left mode is the best constrained, while the bottom right mode is the worst constrained. The middle row gives examples of modes with typical errors. The modes are normalized such that the maximum absolute error is 1. Note that the worst-constrained mode is the exactly degenerate overall zero point of the survey. The structures are similar for the other bands. [*See the electronic edition of the Journal for a color version of this figure.*]

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Calibration in the DES

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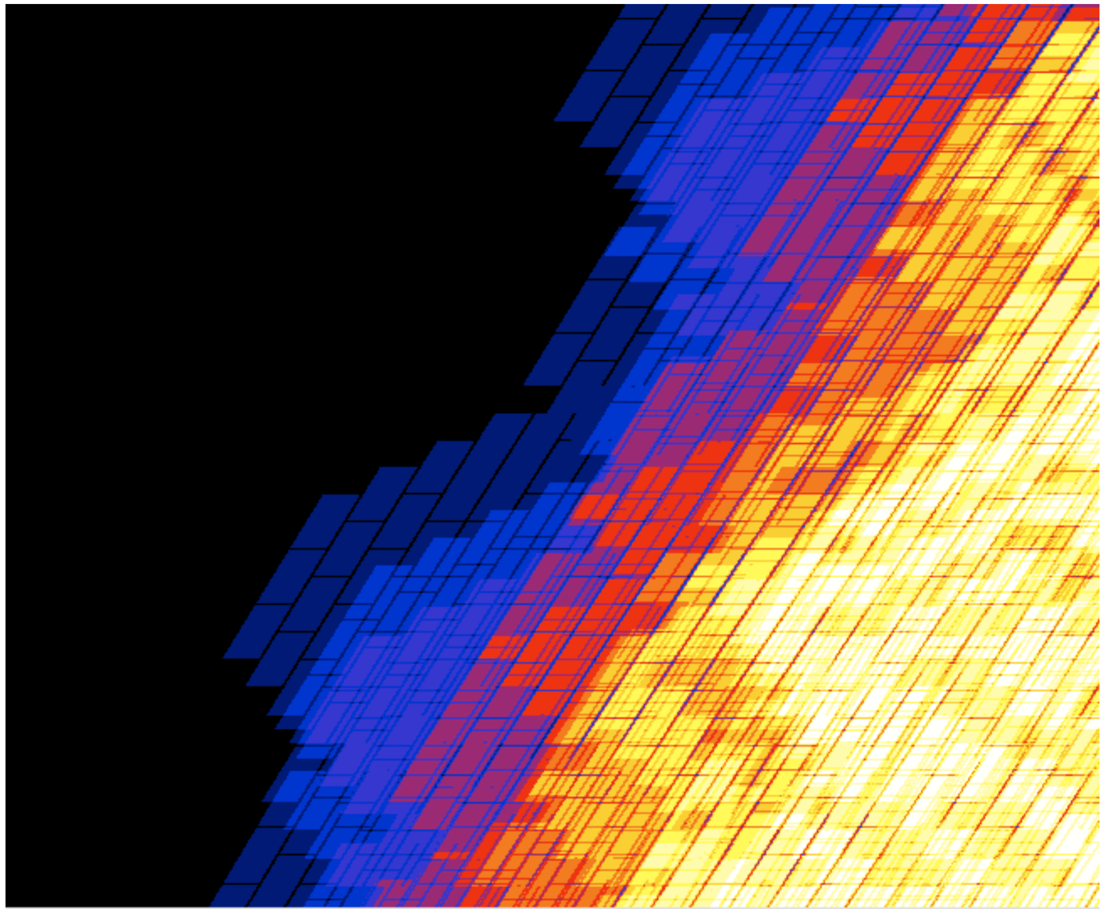
Massive overlapping data

% covered by n tilings

tiles	1	2	3	4	5	6	7	8	9	10
2010	23	79								
2011	5	12	26	64						
2012	2	3	5	15	30	51				
2013		2	3	4	8	17	33	41		
2014				2	3	5	10	19	31	34



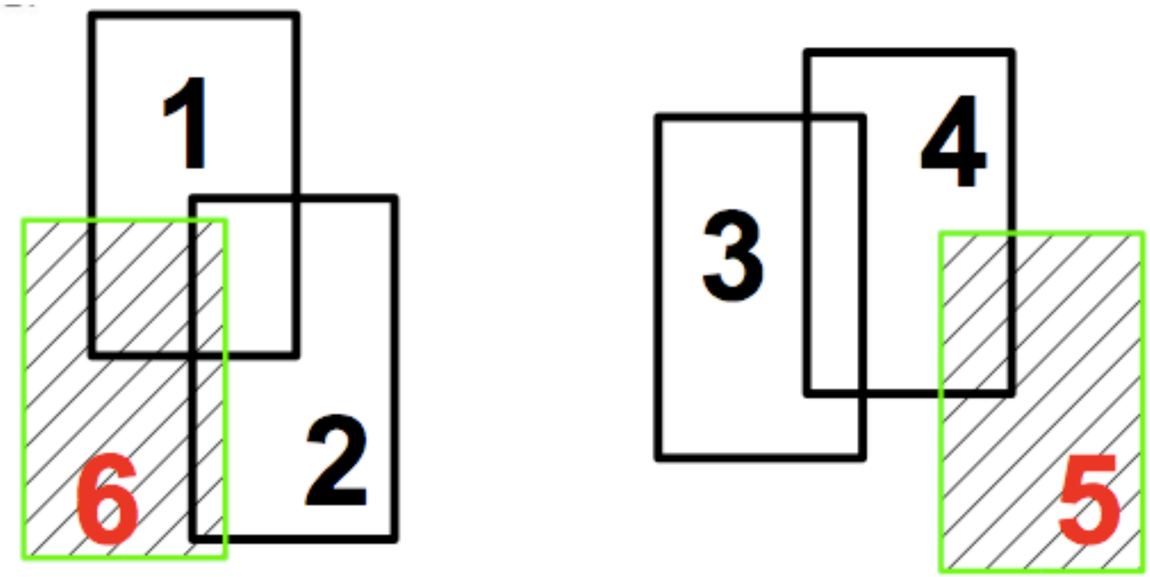
95% of observations taken within 0.17 of airmass 1.17

DARK ENERGY SURVEY

Hybrid method

How DES calibration works:

The calibration plan for the DES uses a hybrid of methods 1 and 2 where all-sky photometry of method 1 is performed when possible. The implementation is due to Glazebrook and coworkers (Glazebrook et al MNRAS 266 65, 1994; see also MacDonald et al MNRAS 352 1255, 2004). Exposures taken on nights when all-sky photometry was performed have their zeropoints in $\boldsymbol{x}$ set to 0: the all sky photometry is explicitly set to truth (despite having dispersion known to be at the ~2% level).



Example:
Frames 5 & 6 are calibrated.
The others are uncalibrated.
(From Glazebrook et al. 1994)

$$\begin{vmatrix} -2 & 1 & 0 & 0 & 0 & 1 \\ 1 & -2 & 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 1 & 0 & 0 \\ 0 & 0 & 1 & -2 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{vmatrix} \times \begin{vmatrix} ZP1 \\ ZP2 \\ ZP3 \\ ZP4 \\ ZP5 \\ ZP6 \end{vmatrix} = \begin{vmatrix} \Delta_{12} + \Delta_{16} \\ \Delta_{21} + \Delta_{26} \\ \Delta_{34} \\ \Delta_{43} + \Delta_{45} \\ 0 \\ 0 \end{vmatrix}$$

If calibrated, assume deviation is zero

From D. Tucker

DARK ENERGY SURVEY

White dwarfs and calibration

1. Assume we have performed internal calibrations, so we have star magnitudes that inside a bandpass have <2% deviations, but with arbitrary zeropoint. This is true for all 5 bandpasses.

2. Assume we have measured precise and accurate system response curves.

3. Assume we can measured T for 100 white dwarfs, can predict spectra for them, and have created m_{wd} for all white dwarfs and bandpasses.

4. Then:

   - Absolute calibration for i-band only

     1. zeropoint(i) = $\Sigma\ (m_{wd} - m_i)/n$

   - Relative calibration for g-i, r-i, i-z, i-y

     1. zeropoint(g-i) = $\Sigma\ ((m_{wd,g} - m_{wd,i}) - (m_{i,g} - m_{i,r}))/n$

DARK ENERGY SURVEY

Precam benefits

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Precam Benefits

Given a Precam survey that produced standard stars observed in a reasonable fraction of main camera pointings, then:

- DECam need not, in normal DES operations, observe other standards
- The frees up DES observation time to observe more of the survey

1\.

1) Observing time that DES would otherwise use to observe standard stars is saved, allowing that much more time for science.

2) The calibration using the standard stars of method 1 is fundamentally better because of the scarcity of standard stars observations in space and time. In the original plan, standard stars are observed only at the beginning, middle, and end of each night, a coarse time sampling when the aim is 2% photometry. Since the atmosphere can change on faster time scales, this uncertainty leads to an irreducible calibration error for a given night. Further, the existing standard stars (with the exception of stripe 82) are sparsely sampled on the DECam focal plane, as opposed to having several on every CCD. Since the calibration can vary across the 2.2-degree field-of-view, this uncertainty also leads to another irreducible calibration error.

DARK ENERGY SURVEY

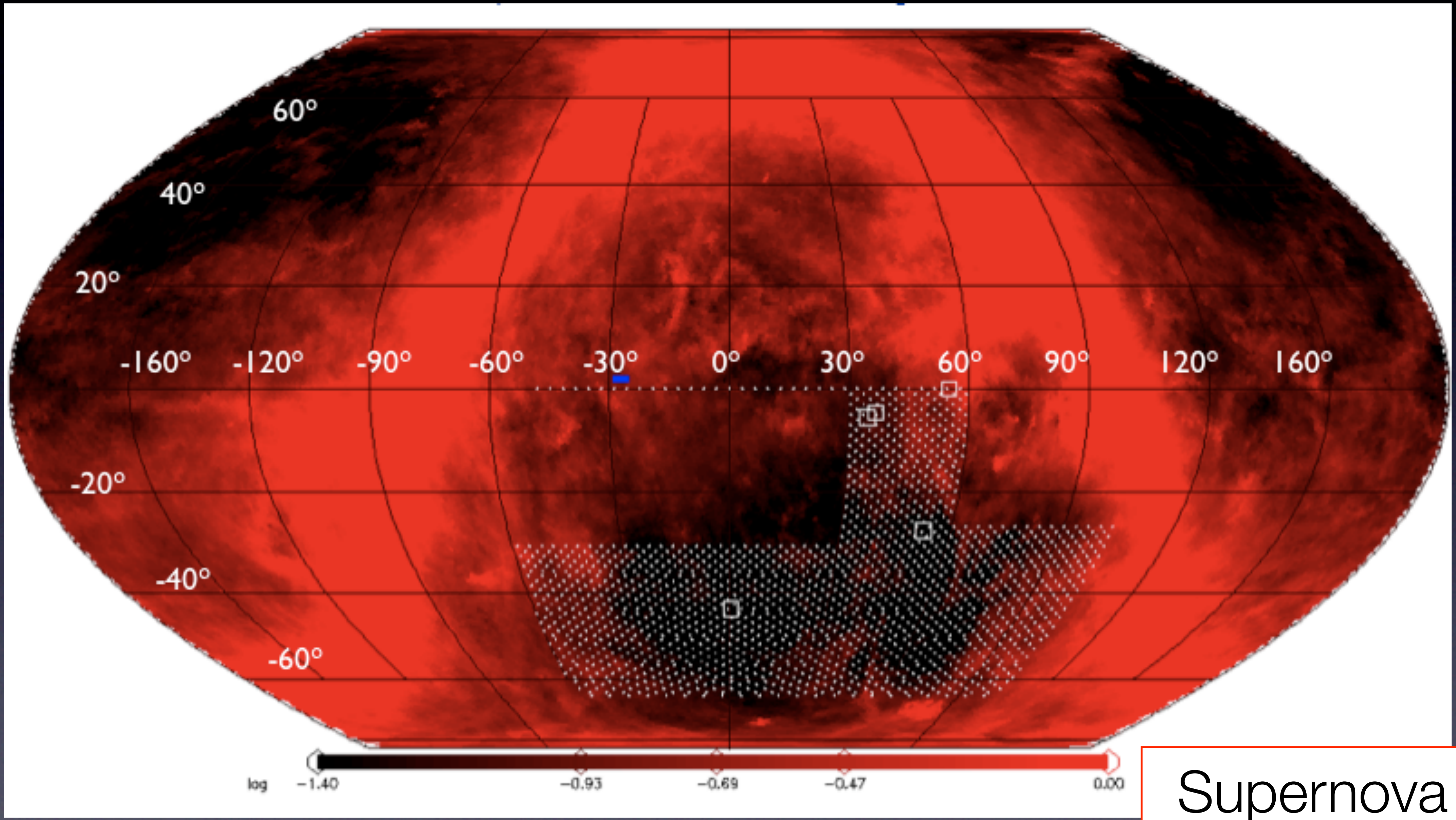
Precam Benefits

2. 3) The calibration using the relative photometry of method 2 is fundamentally of more use to the collaboration because the calibration will be better in survey year 2 and especially year 1 when the number of tilings from the main survey can be supplemented by the small telescope data.

3. Furthermore, let us assume that we can develop a method of producing 1% photometry using the small telescope and that we can map a significant portion of the DES survey area using it. Then:

4) The DES calibration will be better because it can be tested against an external reference standard to check for gradients in photometry East to West or North to South.

The DES Survey



Supernova Fields

	RA	Dec	
CDF South	52.5	-27.5	deep
Stripe 82	55.0	0.0	deep
Elias S1	0.5	-43.5	wide
XMM-LSS	34.5	-5.5	wide
SNLS/VIRM	36.75	-4.5	wide